Spring 2020

Collective effect of landfills and landscape composition on bird–aircraft collisions

Morgan Pfeiffer
USDA, APHIS, Wildlife Services, National Wildlife Research Center, morgan.b.pfeiffer@usda.gov

Bradley F. Blackwell
USDA, APHIS, Wildlife Services, National Wildlife Research Center

Travis L. DeVault
University of Georgia, Aiken

Human–Wildlife Interactions 14(1):43–54, Spring 2020 • digitalcommons.usu.edu/hwi

Collective effect of landfills and landscape composition on bird–aircraft collisions

Morgan B. Pfeiffer, USDA, APHIS, Wildlife Services, National Wildlife Research Center, 6100 Columbus Avenue, Sandusky, OH 44870, USA *morgan.b.pfeiffer@usda.gov*

Bradley F. Blackwell, USDA, APHIS, Wildlife Services, National Wildlife Research Center, 6100 Columbus Avenue, Sandusky, OH 44870, USA

Travis L. DeVault, Savannah River Ecology Laboratory, University of Georgia, Aiken, South Carolina 29802, USA

Abstract: Ninety-three percent of all reported bird strikes occur below 1,067 m, which based on the typical approach and departure angles of aircraft is within 8–13 km of an airport. Concomitantly, the Federal Aviation Administration and the International Civil Aviation Organization recommend that any feature that would attract hazardous wildlife to the approach and departure airspace be restricted. Thus, preventing the establishment of wildlife attractants, such as municipal solid waste landfills (MSWLFs) within 8 km or 13 km extents (U.S. and international recommendations, respectively) of airports, has been recommended to mitigate the risk of bird–aircraft collisions (strikes). However, robust evidence linking wildlife attractants at these spatial scales to an increase in strikes is lacking. We investigated the effect of densities of MSWLFs and construction and demolition (C&D) landfills, landscape diversity, and human population density on the adverse effect (AE; strikes that caused damage or had a negative effect on flight) bird strike rate involving species broadly associated with MSWLFs. We predicted that airports surrounded by a high density of MSWLFs, high human population densities, and high landscape diversity would increase the AE strike rate. We evaluated our predictions via generalized linear mixed models with bird strike data from 2009 through 2017 at 111 Part 139 airports. Only U.S. airports were used because of high wildlife strike reporting rates. Part 139 certificated airports are those that facilitate air carriers with >30 seats for passengers and crew. Our average model included density of MSWLFs and C&D landfills for both the 8- and 13-km extent from the airports. We found no significant contribution by any variable to the AE strike rate variance. Our results indicated that the effects of landfills on AE strike rates are inconclusive. Possible explanations for our findings include the influence of unmeasured landscape features and lack of fine-scale data on bird habitat use at landfill facilities. Future research should investigate bird 3-dimensional space use in addition to bird and habitat survey techniques.

Key words: airport, anthropogenic landscape, aviation, bird strikes, habitat, hazards, landfill

Animals have benefited from food waste provided by humans since prehistoric times (Chamberlain et al. 2005, Morelli et al. 2015). With transition from the nomadic lifestyle to formation of permanent societies, people required locations and means of storing waste (Wilson 2007). Modern waste management activities in the United States operate on unit collection programs, which deliver waste to transfer stations and then eventually deposit the waste at a municipal solid waste landfill (MSWLF; Bovea et al. 2007, Kollikkathara et al. 2009). In 2015, >30 million tons of food waste were deposited in U.S. MSWLFs (Environmental Protection Agency [EPA] 2018). Regular deliveries of food waste to MSWLFs over years have created predictable and clustered food resources for many opportunistic wildlife species (Belant et al. 1995, Oro et al. 2013).

The placement and operation of MSWLFs can alter movement patterns and reproduction rates of wildlife (McKinney 2008, Baxter and Allan 2010, Oro et al. 2013, Gilbert et al. 2016). For example, MSWLFs and agricultural areas are able to support juvenile white storks (*Ciconia ciconia*) over the European winter, which has reduced the number of storks migrating to Africa for invertebrate food resources (Rotics et al. 2017). In Washington's Olympic Peninsula, USA, Marzluff and Neatherlin (2006) reported that American crows (*Corvus brachyrhynchos*) and common ravens (*Corvus corax*) had smaller home ranges and fledged more offspring near human settlements and recreation areas.

Further, annual survival of corvids was positively associated with proximity to human development. In Ohio, USA, approximately 35–55% of a local herring gull (*Larus argentatus*) population was present at an MSWLF during the post-fledgling period (Belant et al. 1993).

Increases in densities of certain species caused by the abundance of anthropogenic food resources at MSWLFs have escalated human–wildlife conflicts (Belant 1997, Araujo et al. 2018). Numerous gull species (*Larus* spp.) visit landfills and can transmit parasites between water sources, damage buildings, and are considered hazardous to aviation (Patton 1988, Belant 1997, Belant et al. 1998, Egunez et al. 2018). Gulls were involved in >11,000 strikes with U.S. civil aircraft from 1990 to 2017, and damage from these strikes resulted in >$60 million in repairs and aircraft downtime (Dolbeer and Begier 2019). Furthermore, strikes with gulls have caused crashes, which resulted in human injuries. (Dolbeer and Begier 2019). Consequently, 2 gull species are listed among the top 10 species that pose the highest strike risk to civil aviation across the United States (DeVault et al. 2018). In addition to gulls, MSWLFs have the potential to attract other birds considered hazardous to aviation, including eagles (Accipitridae), vultures (Cathartidae), geese (Anatidae), and pigeons (Columbidae; International Civil Aviation Organization [ICAO] 2002, Federal Aviation Administration [FAA] 2006, DeVault et al. 2011, Oro et al. 2013).

The FAA and the ICAO acknowledge the hazard posed by MSWLFs and recommend that new MSWLFs not be constructed within 8 (FAA) or 13 (ICAO) km of an airport or in such a location that would attract hazardous wildlife to the approach and departure airspace (FAA 2006, 2007). The recommendation for the minimum separation distances are based on reviews of the National Wildlife Strike Database (NWSD; Dolbeer 2006, DeVault et al. 2013). Ninety-three percent of all reported bird strikes occur below 1,067 m, which based on the typical approach and departure angles of aircraft (3–10°), is within 8 and 13 km of an airport (Flight Safety Foundation 2000, Dolbeer 2006, Van Baren et al. 2017). Also, the FAA considers construction and demolition (C&D) landfills as acceptable within the 8-km extent because they do not handle putrescible waste and therefore should not attract large numbers of birds. However, if the C&D landfill is "not maintained in an orderly manner and has similar visual and operational characteristics to MSWLFs," it might be considered a wildlife attractant and should be located at least 8 km away from an airport (FAA 2007). The presence of C&D landfills with natural surface water and storm water retention ponds (Fox et al. 2013) and an abundance of turf grass or cover for prey (DeVault and Washburn 2013) can create similar wildlife attractants as MSWLFs, which contain these features in addition to municipal food waste. Despite these predictions, there has not been a large-scale investigation that has evaluated the possible effects of landfills on bird strikes across landscapes. The inconsistencies and lack of empirical data supporting these recommendations call for a greater understanding of the influence of MSWLFs and C&D landfills on the bird strike rate.

Previous research indicated that the influence of land use on the strike rate was similar for the 8- and 13-km extents with regard to land-use categories (wetland, crop, water; Pfeiffer et al. 2018). However, strike rates differed in terms of metrics (nearest neighbor distance, patch, and area), likely due to variability in 3-dimensional use of the airspace by birds and aircraft (Dolbeer 2006, Pfeiffer et al. 2018). Interestingly, landscape diversity was a significant predictor for the bird strike rate only at the smallest extent of 3 km, including the airport property (Pfeiffer et al. 2018). However, it is also important to consider discrete wildlife attractants, such as MSWLFs, as part of the surrounding landscape mosaic (Blackwell et al. 2009); density of MSWLFs can potentially interact with aspects of the larger landscape mosaic (Ricketts 2001, Baxter et al. 2003, Pfeiffer et al. 2018). For instance, although not a significant contributor to variation in strike rate, landscape diversity was present in the top models for the 8- and 13-km extents and might also influence the strike rate of wildlife associated with MSWLFs (Pfeiffer et al. 2018).

Another factor that might influence the strike rate of species attracted to landfills is the density of humans. Egyptian vulture (*Neophron percnopterus*) and hooded vulture (*Necrosyrtes monachus*) abundance was best explained by the density of human settlements, with the highest abundance of vultures closest

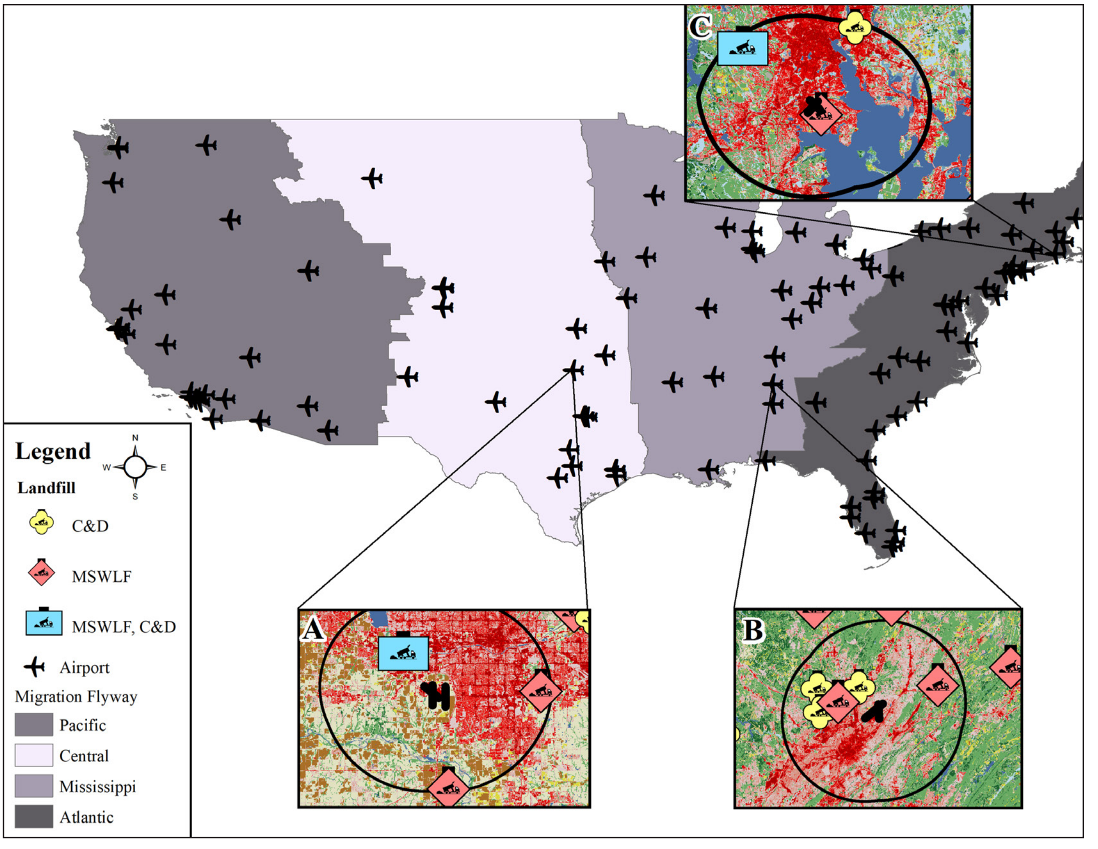

Figure 1. Location of civil airports (*n* = 111) used in the analyses. Example airports are shown in relation to migration flyway in which they were located. (A) is Will Rogers World Airport, Oklahoma City, Oklahoma (OKC), (B) is Birmingham-Shuttlesworth International Airport, Birmingham, Alabama (BHM), and (C) is Providence T.F., Warwick, Rhode Island (PVD), USA. Legend: MSWLF = municipal solid waste landfill; C&D = construction and demolition landfills.

to dense human settlements (Gangoso et al. 2013, Tauler-Ametller et al. 2017, Henriques et al. 2018). Turkey vultures (*Cathartes aura*) and black vultures (*Coragyps atratus*) are considered a high risk to aviation (third and eleventh in the United States, respectively) and are abundant at MSWLFs and waste bins during certain times of the year (Belant et al. 1995, Araujo et al. 2018, DeVault et al. 2018). Furthermore, vultures are efficient at soaring and gain great heights when circling in a thermal (DeVault et al. 2005), which could increase the potential for a bird strike (Walter et al. 2012). Restrictions for constructing MSWLFs near airports specifically stress a possible increased risk of aircraft collisions with vultures, although evidence is speculative (FAA 2006). Further, not all vulture species exhibit a positive association with high human population densities (Krüger et al. 2015, Henriques et al. 2018).

The purpose of our study was to evaluate the influence of landfills in combination with other landscape features on bird strike rates. Based on our research, we provide recommendations regarding future research and management that may better evaluate land uses relative to policy to reduce wildlife hazards to aviation. We hypothesized that the bird strike rate with MSWLF-associated species would differ across airports because of the arrangement of MSWLFs in the surrounding land use mosaics. Specifically, we considered MSWLFs as resource patches within the landscape mosaic of an airport and its surroundings, as defined by landscape ecology (Turner and Gardner 2015). We predicted that: (1) a high density of MSWLFs (~ 0.011 MSWLFs per km^2) and few C&D landfills around airports would lead to a higher adverse effect (AE) strike rate with species associated with landfills because of municipal waste availability;

Table 1. List of species/groups associated with municipal solid waste landfills (MSWLFs). Justification refers to the review paper Oro et al. 2013 (1.) or U.S. Department of Agriculture Wildlife Services data (2.). Adverse effect (AE) strikes per species/group between 2009 and 2017 within 13 km of the sample 111 airports are listed. Species/groups are listed in taxonomic order.

Species/group	Justification	Number of AE strikes
Wood stork (*Mycteria americana*)	1.	2
White-faced ibis (*Plegadis chihi*)	1.	7
Mute swan (*Cygnus olor*)	2.	2
Canada goose (*Branta canadensis*)	2.	95
Mallard (*Anas platyrhynchos*)	2.	63
*New World Vultures (Family: Cathartidae)	1. & 2.	12
Turkey vulture (*Cathartes aura*)	1. & 2.	78
Black vulture (*Coragyps atratus*)	1. & 2.	51
Golden eagle (*Aquila chrysaetos*)	1.	3
Bald eagle (*Haliaeetus leucocephalus*)	1.	26
*Gulls (Family: Laridae)	1. & 2.	102
Franklin's gull (*Leucophaeus pipixcan*)	1. & 2.	4
Laughing gull (*Leucophaeus atricilla*)	1. & 2.	3
Ring-billed gull (*Larus delawarensis*)	1. & 2.	38
Mew gull (*Larus canus*)	1.	1
California gull (*Larus californicus*)	1. & 2.	15
Herring gull (*Larus argentatus*)	1. & 2.	40
Glaucous gull (*Larus hyperboreus*)	1.	2
Western gull (*Larus occidentalis*)	1. & 2.	9
Glaucous-winged gull (*Larus glaucescens*)	1. & 2.	6
Great black-backed gull (*Larus marinus*)	1. & 2.	4
Rock dove (*Columba livia*)	1. & 2.	81
*Crows and Ravens (Family: Corvidae)	2.	4
American crow (*Corvus brachyrhynchos*)	2.	3
European starling (*Sturnus vulgaris*)	2.	60
House sparrow (*Passer domesticus*)	2.	2

* Group of birds not identified to species.

(2) airports surrounded by combined C&D/MSWLFs would have a higher AE strike rate compared to other landscape compositions (no landfills, just C&D landfills, or separate C&D and MSWLF facilities) because of increased food availability and diversity in land uses; (3) greater landscape diversity around airports, in addition to multiple MSWLF and high human population densities, would lead to increases in the AE strike rate (Pfeiffer et al. 2018); and (4) high MSWLF densities and landscape diversity around airports would increase the AE strike rate, irrespective of human population densities. In addition, we predicted that model variables would differ in importance per spatial extent (8 or 13 km), but effect (positive or negative) of the variables would be similar (Pfeiffer et al. 2018).

Methods

Selection of airports

As of August 2018, there were 526 Part 139 certificated airports in the United States and its territories (FAA 2017*a*). Part 139 certificated airports are those that facilitate air carriers with >30 seats for passengers and crew and are required to maintain certain operational/safety standards and create a Wildlife Hazard Management Plan (FAA 2015). John F. Kennedy International Airport in New York City, USA, is an example of a Part 139 airport. We tallied the number of air carrier movements (i.e., takeoffs and landings) per airport per annum using the FAA terminal area forecast (FAA 2017*b*). In our analysis, we included all Part 139 airports with an average of >10,000 air carrier movements per annum from 2009 through 2017. One airport, El Paso International Airport (KELP), Texas, USA, was removed because it was <10 km from the Mexico border and landscape variables were not available for Mexico. In total, we used 111 Part 139 airports (Figure 1) in the analysis. Only U.S. airports were used because of high wildlife strike reporting rates (see below).

Bird strike data

The FAA has recorded wildlife strikes with civil aircraft since 1990 in the NWSD (https://wildlife.faa.gov/). Strike records are submitted by pilots, ground crew, and airport biologists using a standard form (FAA Form 5200-7) or online (https://wildlife.faa.gov/strikenew.aspx) and are reviewed for quality control (Dolbeer 2015). Although strike reporting to the NWSD is largely voluntary, between 2009 and 2013 the NWSD received approximately 93% of all damaging bird strike records with civil air carriers at Part 139 airports (Dolbeer 2015). Following the forced landing of Flight 1549 in the Hudson River in 2009 after the aircraft ingested multiple Canada geese (*Branta canadensis*) and associated media coverage of the event, there was an increase in wildlife strike reporting to the NWSD (https://www.faa.gov/news/updates/?newsId=83405). We only used bird strikes in our analysis because mammals can be excluded from airports effectively with fencing (Schwarz et al. 2014) and do not exibit restricted movements between roosts and landfills, which can be hazardous to aviation (Baxter et al. 2003).

We only included bird strikes with species/groups that used MSWLFs (Table 1; Figure 2). We paired species involved with suspected use of MSWLFs by conducting a literature search involving Google Scholar, Scopus, and Web of Science using the terms: bird, wildlife, with either municipal solid waste, or landfill on November 9, 2018 (see Oro et al. 2013 and citations within). To increase our sample size, we also queried the U.S. Department of Agriculture's Wildlife Services Management Information System (MIS) database. Wildlife Services personnel often work at MSWLFs and record the legal lethal take or dispersal of wildlife species. Relative to the MIS, we included only species that were lethally removed or dispersed by Wildlife Services from MSWLFs at least 20 times across landfills. We used this criterion to account for species that were only observed once at a landfill.

Next, for each airport we only included AE strikes with civil air carriers between 2009 and 2017 that involved species/groups associated with MSWLFs. Adverse effect strikes caused damage to the aircraft and/or had a negative effect on the aircraft's flight (Dolbeer 2017). We partitioned the strike data on altitude (above ground level, AGL) and distance from airport into 2 datasets: (1) all AE strikes with birds associated with MSWLFs that occurred within 8 km from the airport (within 8 km and between 157 m and 1,410 m); and (2) all AE strikes with birds associated with MSWLFs that occurred within 13 km from the airport, including the 8-km extent for each airport (within 13 km and between 157 m and 2,292 m). Altitudes were based on the range of angles (3–10°) used in civil aviation for take-off and landing procedures (Flight Safety Foundation 2000, Van Baren et al. 2017, Pfeiffer et al. 2018,). We calculated the AE strike rate (Dolbeer 2017, Pfeiffer et al. 2018) for each airport at each extent using the following equation:

$$\text{AE strike rate} = (\text{total AE strikes} / \text{total air carrier movements}) \times 10{,}000 \quad (1)$$

Landfill characteristics

We obtained spatial data on MSWLFs from the Homeland Infrastructure Foundation Level Data (HIFLD 2017), which covers the United States and was last validated April 2018 (HIFLD 2017). Only MSWLFs and C&D landfills that listed their status as "open" were used for analysis. We calculated landfill density (number per km) by dividing the number of each landfill (MSWLFs or C&D) by the area of the spatial extent (8 or 13 km) for each airport. As some extents contained >1 type of landfill, we consolidated types based

Figure 2. Example of bird use of a municipal solid waste landfill. The image was taken using a DJI Mavic at the Erie County Landfill, Ohio, USA (*photo courtesy of N. Wilson*).

on our prediction that landfills that handle municipal waste, as compared to C&D landfills, would increase strike rates. For example, if an airport was surrounded by both a C&D and MSWLF facility, we recorded the type of landfill for that airport as "both." Likewise, airports with only C&D sites were considered "C&D" and those with MSWLF or joint use MSWLF/C&D were considered "MSWLF." Airports with no landfills within the 2 spatial extents were considered "none."

Landscape mosaic characteristics

We calculated landscape diversity as per Pfeiffer et al. (2018) using the National Land Cover Dataset, which classifies land use at a 30 x 30-m spatial resolution (Homer et al. 2015). We used FRAGSTATS (McGarigal et al. 2012) to calculate the modified Simpson's diversity index (proportion of the landscape occupied by patch type) of land use within the 8- and 13-km extents. Human population density data were obtained for 2010 and 2015 from the National Aeronautics and Space Administration's Socioeconomic Data and Application Center (Center for International Earth Science Information Network 2016). The spatial resolution was 2.5 arc-minute (about 4.5 km at the equator). We obtained total human population density for the study period (2009 to 2017) by calculating the mean of the 2010 and 2015 raster datasets in ArcGIS (Environmental Systems Research Institute 2015). We then added the value of each pixel that was obtained in the 8- and 13-km extents. Therefore, human population density represented the density across each extent (226–455 km^2 for the 8-km extent and 557–901 km^2 for the 13-km extent; variations in areas are the result of airport runway characteristics). Although land use data were static, while bird strikes were continually being reported, this separation was not thought to influence the results because most land use changes within these extents represented a small percentage of the total area.

Statistical analyses

We calculated Spearman's correlation coefficient for each pair of continuous predictor variables and removed one of a pair with significant correlation ($|\rho| > 0.50$, $P < 0.05$). We constructed 7 generalized linear mixed models based on our *a priori* predictions, with the AE strike rate as the response variable for the 8- and 13-km extents. We assumed a Gaussian distribution and used an identity link. Predictor variables included density of MSWLF and C&D sites, type of landfill within the extent (MSWLF, C&D, both, or none), landscape diversity, and human population density. To account for variation in the spatial distribution of species/groups and other resources, we included migration flyway (Atlantic, Mississippi, Central, and Pacific) in which each airport was located within as a random effect. An intercept only and full model containing all non-correlated predictor variables were also constructed. Models were ranked by the Akaike Information Criterion (AIC_c) adjusted for small sample sizes (Burnham and Anderson 2003). We considered models ≤2 ΔAIC as the best fit models for explaining variable influence on the AE strike rate (Burnham and Anderson 2003). Akaike weights (w_i) were used to assess model performance (relative likelihood). Also, because of the policy advocated by the FAA regarding both C&D and MSWLFs (FAA 2006, 2007), we also considered model averaging. Specifically, as predictor variables were collected on the same scale, were uncorrelated and did not interact, model averaging among top models was possible (Cade 2015). We standardized predictor variables by 2 standard deviations to assist model averaging (Gelman 2008). Confidence intervals (95%) were used to evaluate the importance of the predictor variables in the top models, with variable intervals that overlap zero treated as weak relationships (Burnham and Anderson 2004). We used the "lmer," "model.sel," "model.ave,"

Table 2. Results from the generalized linear mixed models of landscape and landfill characteristics (including construction and demolition [C&D]) that influence the adverse effect (AE) strike rate with species/groups associated with municipal solid waste landfills (MSWLFs) within the (A) 8-km and (B) 13-km extent of 111 civil airports in the United States (df = degrees of freedom; logLik = model's loglikelihood value; w_i = Akaike weight).

		df	logLik	AIC_c	ΔAIC_c	w_i
(A) 8-km extent models	Density of C&D landfills*	4	20.89	-33.4	0.00	0.49
	Density of MSWLFs*	4	20.75	-33.1	0.28	0.42
	Null model	3	17.57	-28.9	4.48	0.05
	Density of MSWLFs + landscape diversity	5	19.53	-28.5	4.92	0.04
	Type of landfill	7	11.18	-7.30	26.12	0.00
	Density of MSWLFs + human population density	5	8.29	-6.00	27.40	0.00
	Density of MSWLFs + landscape diversity + human population density	6	6.91	-1.00	32.38	0.00
(B) 13-km extent models	Density of MSWLFs*	4	21.26	-34.1	0.00	0.46
	Density of C&D landfills*	4	21.15	-33.9	0.21	0.42
	Density of MSWLFs + landscape diversity	5	20.60	-30.6	3.51	0.08
	Null model	3	17.63	-29.0	5.09	0.04
	Type of landfill	7	11.36	-7.60	26.51	0.00
	Density of MSWLFs + human population density	5	8.15	-5.70	28.42	0.00
	Density of MSWLFs + landscape diversity + human population density	6	7.21	-1.60	32.53	0.00

*Top model ($\Delta AIC_c \leq 2$)

"standardize," and the "confint" functions in the "lme4" (Bates et al. 2018), "MuMIn" (Barton 2018) and "arm" packages (Gelman and Su 2016) in R 3.5.1 (R Core Team 2018).

Results

At our sample airports within our filtered dataset, 685 AE bird strikes were reported within 8 km between 2009 and 2017. The species/groups associated with MSWLFS that were reported most frequently as struck by aircraft at the sample airports were gulls (n = 97), Canada geese (n = 89), and rock doves (*Columba livia*; n = 81). There were 38 MSWLFs and 32 C&D landfills located within 8 km of our sample airports. Two airports had 3 MSWLFs, and 35% of airports had at least 1 MSWLF or C&D landfill within 8 km. Within 13 km of the sample airports, 713 AE strikes with birds associated with MSWLFs were reported between 2009 and 2017. Gulls (n = 102), Canada geese (n = 95), and rock doves (n = 81) were reported most frequently as struck. There were 86 MSWLFs and 61 C&D landfills located within 13 km of our sample airports. Eight airports had 3 or more MSWLFs, and the majority (62%) had at least one MSWLF or C&D landfill within 13 km. Ten airports had overlapping 13-km extents, but this did not influence the results (Pfeiffer et al. 2018).

For the 8-km extent, the 2 top models were density of MSWLFs and density of C&D landfills, each representing <50% of variation in the AE strike data (Table 2). Density of MSWLFs and density of C&D landfills were not correlated (r_s = 0.18, P = 0.07), and the 2 models were within 0.25 ΔAIC. Because the 95% confidence intervals of the model averaged predictor variables overlapped zero, we cannot infer whether the predictor variables influenced the AE strike rate (Table 3).

For the 13-km extent, the 2 top models were density of MSWLFs and density of C&D landfills, which was similar to the 8-km extent (Table 2). Likewise, neither of the predictor variables were significant at influencing the AE strike rate (Table 3). Density of MSWLFs and density of C&D landfills were also not correlated at this extent (r_s = 0.12, P = 0.23), and were within

Table 3. Model-averaged coefficients and 95% confidence intervals for predicting the probability of a higher adverse effect strike rate with species/groups associated with municipal solid waste landfills (MSWLFs) and construction and demolition (C&D) landfills.

Model	Predictor variable	Estimate[a]	Unconditional se	*z* value	Confidence intervals 2.5%	Confidence intervals 97.5%	RI[b]
8-km extent	Intercept	0.11	0.02	5.02	0.07	0.16	-
	Density of C&D landfills	-0.02	0.03	0.50	-0.11	0.05	0.54
	Density of MSWLFs	0.008	0.03	0.30	-0.09	0.09	0.46
13-km extent	Intercept	0.12	0.02	5.15	0.07	0.16	-
	Density of MSWLF	-0.01	0.03	0.39	-0.10	0.05	0.52
	Density of C&D landfills	-0.01	0.03	0.32	-0.10	0.06	0.48

[a] Effect sizes have been standardized by 2 standard deviations following Gelman (2008).
[b] Relative importance.

0.21 ΔAIC. Again, biologically relevant inference was not possible because of the overlap of the model averaged predictor variables' confidence intervals with zero (Table 3).

Discussion

Despite FAA and ICAO warnings against siting of new MSWLFs and C&Ds within the 8- and 13-km extents of an airport, our analysis found little evidence supporting an association between increased adverse effect bird strikes and the presence of MSWLFs. Specifically, the AE strike rate was influenced similarly at the 8- and 13-km extents by MSWLFs and C&Ds, but each model explained <50% of variation in strikes and confidence intervals of parameter estimates overlapped zero. We consider explanations for our findings and implications for current FAA and ICAO policy and future research below.

Presence and density of MSWLFs and C&Ds were likely associated with unmeasured landscape and urban infrastructure features that might better explain bird use and, subsequently, AE strikes. Specifically, resources that affect habitat use by gulls, Canada geese, and doves (e.g., surface water, urban lawns, and agriculture) could be closely associated with MSWLFs or C&Ds, but these landscape features must be quantified in addition to density estimates of landfills. For example, the magnitude of the effect of MSWLFs on vulture abundance was larger in developing countries (e.g., Brazil, Yemen, and Guinea-Bissau) than that typically observed at U.S. waste collection sites (Kollikkathara et al. 2009, Gangoso et al. 2013, Araujo et al. 2018, Henriques et al. 2018). The maximum count of turkey vultures at a MSWLF over 1 year in the United States was 90 individuals (Belant et al. 1995), whereas at a waste container in Brazil, the maximum count of black vultures was 810 individuals (Araujo et al. 2018). Health and environmental regulations likely differ in these regions, which alter the amount of food scraps available at these sites (Kollikkathara et al. 2009, Gangoso et al. 2013).

Furthermore, bird use of MSWLFs is ephemeral (Belant et al. 1993, Coulson 2015). To account for the unknown distribution of other resources, we included migration flyway as a random effect, but this effect was likely too broad to capture the local-level influences of landscape features associated with the target landfill types. In addition, by not addressing seasonal effects that require fine-scale data on habitat use by birds at landfill facilities and associated landscape characteristics (Washburn 2012), our models did not incorporate this likely temporality. Importantly, quantifying these additional metrics requires a standardization of avian survey methodology across seasons on airports and surrounding properties (Blackwell et al. 2013), in addition to a standardized sampling protocol for assessing resource availability of target habitat features.

Another possible explanation for lack of significant findings is the lower occurrence/reporting of bird strikes 8 km away from an airport. For our study period and airports, we increased our sample size by only 28 AE strikes (4%) from the 8- to 13-km extent despite increasing our sampling area by a factor of 2.6. Although reporting of AE strikes is higher than strikes without damage or an effect on flight (Dolbeer 2015), reporting might differ based on distance from the airport. Also, in addition to possible lower reporting rates, aircraft are generally higher than the most bird-rich altitudes (~0–1,067 m AGL) at 8 km from an airport (Dolbeer 2006). Based on the minimum (3°) glide slope and a maximum (10°) departure gradient for landing and departing aircraft, respectively, the possible range of altitudes for aircraft 8 km out could be ~419–1,400 m AGL (Flight Safety Foundation 2000, Van Baren et al. 2017). For example, this altitude range is generally above the average flying altitudes of turkey vultures and black vultures (DeVault et al. 2005, Avery et al. 2011), Canada geese (Rutledge et al. 2015), and some gull species (Shamoun-Baranes et al. 2006).

Alternatively, a high abundance/density of feeding sites (MSWLFs) could encourage lower altitude flight than if there were fewer MSWLFs (Spiegel et al. 2013). In other words, species/groups associated with MSWLFs might fly at lower altitudes than aircraft in landscapes with more MSWLFs (because of resource proximity and satiation) and would not compete for airspace with aircraft traveling at higher altitudes (Brown 1988, Spiegel et al. 2013). Details of aircraft and bird 3-dimensional movements in relation to landscape and MSWLF characteristics could enhance the fit of models in subsequent analyses (Walter et al. 2012).

Management implications

Although our analysis, considering the constraints, found no association between adverse effect bird strikes and landfills, we do not conclude that all landfills pose no danger to aviation. Rather, our results point to the need for more detailed data on bird abundance and movements around airports and landfills, especially in 3 dimensions. These data could allow for more targeted analyses that can better describe bird use of these resources and possible risk to aircraft in departure and arrival corridors. These analyses could then allow for better policy recommendations for wildlife strike mitigation. Further research in this area could point to land use planning recommendations that would support wildlife management decisions, prevent unnecessary waste infrastructure zoning projects, and create solutions for the shortage of suitable landfill placement locations.

Acknowledgments

We thank J. Washburn, S. Alls, R. Myer, B. Wilmoth, M. Foster, A. Guikema, J. Nave, K. Stucker, R. Hale, S. Beckerman, J. Rumbaugh, D. Allaben, A. Duffiney, S. Smith, D. LeBlanc, R. Dyer, D. Hirchert, M. Chandler, N. Myers, J. Steuber, A. Montoney, J. Forbes, and T. Booth for data acquisition. We thank M. Drabik-Hamshare and C. T. Downs for reviews of an earlier version of this manuscript. Research was supported by the Federal Aviation Administration (FAA) and U.S. Department of Agriculture Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Center. Results of this study do not necessarily reflect current FAA policy decisions governing the regulation of wildlife and land uses on or near airports. Comments provide by 2 anonymous reviewers and F. Angelici, HWI associate editor, greatly improved earlier versions of this manuscript.

Literature cited

Araujo, G. M. D., C. A. Peres, F. B. Baccaro, and R. S. Guerta. 2018. Urban waste disposal explains the distribution of black vultures (*Coragyps atratus*) in an Amazonian metropolis: management implications for birdstrikes and urban planning. PeerJ 6:e5491.

Avery, M. L., J. S. Humphrey, T. S. Daughtery, J. W. Fischer, M. P. Milleson, E. A. Tillman, W. E. Bruce, and W. D. Walter. 2011. Vulture flight behavior and implications for aircraft safety. Journal of Wildlife Management 75:1581–1587.

Barton, K. 2018. MuMIn: multi-model inference. R package version 1.42.1. R Foundation for Statistical Computing, Vienna, Austria.

Bates, D., M. Maechler, B. Bolker, and S. Walker. 2018. lme4: Linear mixed-effects models using Eigen and S4. R package version 1.1–17. R Foundation for Statistical Computing, Vienna, Austria.

Baxter, A. T., and J. R. Allan. 2010. Use of raptors to reduce scavenging bird numbers at landfill sites. Wildlife Society Bulletin 34:1162–1168.

Baxter, A. T., K. S. James, R. Thompson, and H. Laycock. 2003. Predicting the birdstrike hazard from gulls at landfill sites. International Bird Strike Committte, Warsaw, Poland.

Belant, J. L. 1997. Gulls in urban environments: landscape-level management to reduce conflict. Landscape and Urban Planning 38:245–258.

Belant, J. L., S. K. Ickes, and T. W. Seamans. 1998. Importance of landfills to urban-nesting herring and ring-billed gulls. Landscape and Urban Planning 43:11–19.

Belant, J. L., T. W. Seamans, S. W. Gabrey, and R. A. Dolbeer. 1995. Abundance of gulls and other birds at landfills in northern Ohio. American Midland Naturalist 134:30–40.

Belant, J. L., T. W. Seamans, S. W. Gabrey, and S. K. Ickes. 1993. Importance of landfills to nesting herring gulls. Condor 95:817–830.

Blackwell, B. F., T. L. DeVault, E. Fernández-Juricic, and R. A. Dolbeer. 2009. Wildlife collisions with aircraft: a missing component of land-use planning for airports. Landscape and Urban Planning 93:1–9.

Blackwell, B. F., P. M. Schmidt, and J. A. Martin. 2013. Avian survey methods for use at airports. Pages 153–165 *in* T. L. DeVault, B. F. Blackwell, and J. L. Belant, editors. Wildlife in airport environments. John Hopkins University Press, Baltimore, Maryland, USA.

Bovea, M., J. Powell, A. Gallardo, and S. Capuz-Rizo. 2007. The role played by environmental factors in the integration of a transfer station in a municipal solid waste management system. Waste Management 27:545–553.

Brown, J. S. 1988. Patch use as an indicator of habitat preference, predation risk, and competition. Behavioral Ecology and Sociobiology 22:37–47.

Burnham, K. P., and D. R. Anderson. 2003. Model selection and multimodel inference: a practical information-theoretic approach. Springer Science & Business Media, New York, New York, USA.

Burnham, K. P., and D. R. Anderson. 2004. Multimodel inference: understanding AIC and BIC in model selection. Sociology Methods and Research 33:261–304.

Cade, B. S. 2015. Model averaging and muddled multimodel inferences. Ecology 96:2370–2382.

Center for International Earth Science Information Network. 2016. Gridded Population of the World, version 4 (GPWv4): population density. National Aeronautics and Space Administration Socioeconomic Data and Applications Center, Columbia University, New York, New York, USA.

Chamberlain, C., J. Waldbauer, K. Fox-Dobbs, S. Newsome, P. Koch, D. Smith, M. Church, S. Chamberlain, K. Sorenson, and R. Risebrough. 2005. Pleistocene to recent dietary shifts in California condors. Proceedings of the National Academy of Science 102:16707–16711.

Coulson, J. C. 2015. Re-evaluation of the role of landfills and culling in the historic changes in the herring gull (*Larus argentatus*) population in Great Britain. Waterbirds 38:339–354.

DeVault, T. L., J. L. Belant, B. F. Blackwell, and T. W. Seamans. 2011. Interspecific variation in wildlife hazards to aircraft: implications for airport wildlife management. Wildlife Society Bulletin 35:394–402.

DeVault, T. L., B. F. Blackwell, and J. L. Belant. 2013. Wildlife in airport environments: preventing animal–aircraft collisions through science-based management. John Hopkins University Press, Baltimore, Maryland, USA.

DeVault, T. L., B. F. Blackwell, T. W. Seamans, M. Begier, J. D. Kougher, J. Washburn, P. Miller, and R. A. Dolbeer. 2018. Estimating interspecific economic risk of bird strikes with aircraft. Wildlife Society Bulletin 42:94–101.

DeVault, T. L., B. D. Reinhart, I. L. Brisbin, and O. E. Rhodes. 2005. Flight behavior of black and turkey vultures: implications for reducing bird–aircraft collisions. Journal of Wildlife Management 69:601–608.

DeVault, T. L., and B. E. Washburn. 2013. Identification and management of wildlife food resources at airports. Pages 79–90 *in* T. L. DeVault, B. F. Blackwell, and J. L. Belant, editors. Wildlife in airport environments: preventing animal–aircraft collisions through science-based management. Johns Hopkins University Press, Baltimore, Maryland, USA.

Dolbeer, R. A. 2006. Height distribution of birds recorded by collisions with civil aircraft. Journal of Wildlife Management 70:1345–1350.

Dolbeer, R. A. 2015. Trends in reporting of wildlife strikes with civil aircraft and in identification of species struck under a primarily voluntary reporting system, 1990–2013. Federal Aviation Administration, Washington, D.C., USA.

Dolbeer, R. A. 2017. Comparison of adverse effect strikes and damage strikes as benchmarks for Wildlife Hazard Management Plans at Part 139-certificated airports. Airport Wildlife Hazards Program, U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, Huron, Ohio, USA.

Dolbeer, R. A., and M. J. Begier. 2019. Wildlife strikes to civil aircraft in the United States, 1990–2017. Federal Aviation Administration, Washington, D.C., USA.

Egunez, A., N. Zorrozua, A. Aldalur, A. Herrero, and J. Arizaga. 2018. Local use of landfills by a yellow-legged gull population suggests distance-dependent resource exploitation. Journal of Avian Biology 49:jav-01455.

Environmental Protection Agency (EPA). 2018. Advancing sustainable materials management: 2015 fact sheet. United States Environmental Protection Agency, Washington, D.C., USA.

Environmental Systems Research Institute. 2015. ArcGIS 10.4 for Desktop, Version: 10.4.0.5524 ed. Environmental Systems Research Institute, Inc., Redlands, California, USA.

Federal Aviation Administration (FAA). 2006. Construction or establishment of landfills near public airports. Federal Aviation Administration, Washington, D.C., USA.

Federal Aviation Administration (FAA). 2007. Hazardous wildlife attractants on or near airports, Advisory Circular 150/5200-33B. U.S. Department of Transportation, Washington, D.C., USA.

Federal Aviation Administration (FAA). 2015. What is Part 139? Part 139 airport certification. Federal Aviation Administration, Washington, D.C., USA.

Federal Aviation Administration (FAA). 2017*a*. Part 139 airport certification status list (ACSL). Federal Aviation Administration, Washington, D.C., USA.

Federal Aviation Administration (FAA). 2017*b*. Terminal area forecast (TAF) system. Federal Aviation Administration, Washington, D.C., USA.

Flight Safety Foundation. 2000. Flight Safety Foundation approach-and-landing accident reduction briefing note 4.2-energy management. Flight Saftey Digest August:75–80.

Fox, B. J., W. B. Holland, F. L. Boyd, B. F. Blackwell, and J. B. Armstrong. 2013. Use of stormwater impoundments near airports by birds recognized as hazardous to aviation safety. Landscape and Urban Planning 119:64–73.

Gangoso, L., R. Agudo, J. D. Anadón, M. de la Riva, A. S. Suleyman, R. Porter, and J. A. Donázar. 2013. Reinventing mutualism between humans and wild fauna: insights from vultures as ecosystem services providers. Conservation Letters 6:172–179.

Gelman, A. 2008. Scaling regression inputs by dividing by two standard deviations. Statistics in Medicine 27:2865–2873.

Gelman, A., and Y. Su. 2016. arm: Data analysis using regression and multilevel/hierarchical models. R package version 1.8-6. 2015. R Foundation for Statistical Computing, Vienna, Austria.

Gilbert, N. I., R. A. Correia, J. P. Silva, C. Pacheco, I. Catry, P. W. Atkinson, J. A. Gill, nd A. M. Franco. 2016. Are white storks addicted to junk food? Impacts of landfill use on the movement and behaviour of resident white storks (*Ciconia ciconia*) from a partially migratory population. Movement Ecology 4:7.

Henriques, M., J. P. Granadeiro, H. Monteiro, A. Nuno, M. Lecoq, P. Cardoso, A. Regalla, and P. Catry. 2018. Not in wilderness: African vulture strongholds remain in areas with high human density. PLOS ONE 13(1):e0190594.

Homeland Infrastructure Foundation Level Data (HIFLD) 2017. Solid waste landfill facilities. U.S. Department of Homeland Security, Washington, D.C, USA.

Homer, C. G., J. A. Dewitz, L. Yang, S. Jin, P. Danielson, G. Xian, J. Coulston, N. D. Herold, J. Wickham, and K. Megown. 2015. Completion of the 2011 National Land Cover Database for the conterminous United States—representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing 81:345–354.

International Civil Aviation Organization (ICAO). 2002. Airport planning manual, 9184 AN/902. Part 2. Montreal, Quebec, Canada.

Kollikkathara, N., H. Feng, and E. Stern. 2009. A purview of waste management evolution: special emphasis on USA. Waste Management 29:974–985.

Krüger, S. C., R. E. Simmons, and A. Amar. 2015. Anthropogenic activities influence the abandonment of bearded vulture (*Gypaetus barbatus*) territories in southern Africa. Condor 117:94–107.

Marzluff, J. M., and E. Neatherlin. 2006. Corvid response to human settlements and campgrounds: causes, consequences, and challenges for conservation. Biological Conservation 130:301–314.

McGarigal, K., S. Cushman, and E. Ene. 2012. FRAGSTATS v4: spatial pattern analysis program for categorical and continuous maps. University of Massachusetts, Amherst, Massachusetts, USA.

McKinney, M. L. 2008. Effects of urbanization on species richness: a review of plants and animals. Urban Ecosystems 11:161–176.

Morelli, F., A. M. Kubicka, P. Tryjanowski, and E. Nelson. 2015. The vulture in the sky and the hominin on the land: three million years of human–vulture interaction. Anthrozoös 28:449–468.

Oro, D., M. Genovart, G. Tavecchia, M. S. Fowler, and A. Martínez-Abraín. 2013. Ecological and evolutionary implications of food subsidies from humans. Ecology Letters 16:1501–1514.

Patton, S. R. 1988. Abundance of gulls at Tampa Bay landfills. Wilson Bulletin 100:431–442.

Pfeiffer, M. B., J. D. Kougher, and T. L. DeVault. 2018. Civil airports from a landscape perspective: a multi-scale approach with implications for reducing bird strikes. Landscape and Urban Planning 176:38–45.

R Core Team. 2018. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ricketts, T. H. 2001. The matrix matters: effective isolation in fragmented landscapes. American Naturalist 158:87–99.

Rotics, S., S. Turjeman, M. Kaatz, Y. S. Resheff, D. Zurell, N. Sapir, U. Eggers, W. Fiedler, A. Flack, and F. Jeltsch. 2017. Wintering in Europe instead of Africa enhances juvenile survival in a long-distance migrant. Animal Behavior 126:79–88.

Rutledge, M. E., C. E. Moorman, B. E. Washburn, and C. S. Deperno. 2015. Evaluation of resident Canada goose movements to reduce the risk of goose–aircraft collisions at suburban airports. Journal of Wildlife Mangement 79:1185–1191.

Schwarz, K. B., J. L. Belant, J. A. Martin, T. L. DeVault, and G. Wang. 2014. Behavioral traits and airport type affect mammal incidents with U.S. civil aircraft. Environmental Management 54:908–918.

Shamoun-Baranes, J., E. van Loon, H. van Gastere, J. van Belle, W. Bouten, and L. Buurma. 2006. A comparative analysis of the influence of weather on the flight altitudes of birds. Bulletin of the American Meterological Society 87:47–62.

Spiegel, O., R. Harel, W. M. Getz, and R. Nathan. 2013. Mixed strategies of griffon vultures' (*Gyps fulvus*) response to food deprivation lead to a hump-shaped movement pattern. Movement Ecology 1:5.

Tauler-Ametller, H., A. Hernández-Matías, J. L. Pretus, and J. Real. 2017. Landfills determine the distribution of an expanding breeding population of the endangered Egyptian vulture *Neophron percnopterus*. Ibis 159:757–768.

Turner, M. G., and R. H. Gardner. 2015. Landscape ecology in theory and practice: pattern and process. Second edition. Springer-Verlag, New York, New York, USA.

Van Baren, G., V. Treve, F. Rooseleer, P. Van der Geest, and B. Heesbeen. 2017. Assessing the severity of wake encounters in various aircraft types in piloted flight simulations. American Institute of Aeronautics and Astronautics Modeling and Simulation Technologies Conference, Grapevine, Texas, USA.

Walter, W. D., J. W. Fischer, J. S. Humphrey, T. S. Daughtery, M. P. Milleson, E. A. Tillman, and M. L. Avery 2012. Using three-dimensional flight patterns at airfields to identify hotspots for avian–aircraft collisions. Applied Geography 35:53–59.

Washburn, B. E. 2012. Avian use of solid waste transfer stations. Landscape and Urban Planning 104:388–394.

Wilson, D. C. 2007. Development drivers for waste management. Waste Mangement Research 25:198–207.

Associate Editor: Francesco M. Angelici

Morgan B. Pfeiffer is a postdoctoral researcher at the USDA, APHIS, Wildlife Services, National Wildlife Research Center in Sandusky, Ohio. Her research interests include understanding species plasticity, movements, and behavior in anthropogenic landscapes. Her current research involves evaluating unmanned aircraft systems (UAS) technology for wildlife hazard management.

Bradley F. Blackwell (photo unavailable) serves as a research wildlife biologist for the USDA, APHIS, Wildlife Services, National Wildlife Research Center, Ohio Field Station. His research interests center on animal sensory ecology, antipredator behavior, and means of exploiting sensory pathways and behavior to mitigate problems associated human–wildlife interactions.

Travis L. DeVault is the associate director for research at the University of Georgia's Savannah River Ecology Laboratory in Aiken, South Carolina and holds a graduate faculty appointment in the Warnell School of Forestry & Natural Resources. His research interests in the fields of wildlife ecology, conservation, and behavior focus on the causes and consequences of animal–vehicle collisions and the development of tools and strategies to reduce collisions.